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(54) **VOLTAGE-LEVELING HEATER CABLE**

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H05B 3/14 (2006.01)
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(52) **U.S. Cl.**

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CPC . H05B 3/56; H05B 3/145; H05B 3/12; H05B 3/10; H05B 3/34; H05B 2203/017;

(Continued)

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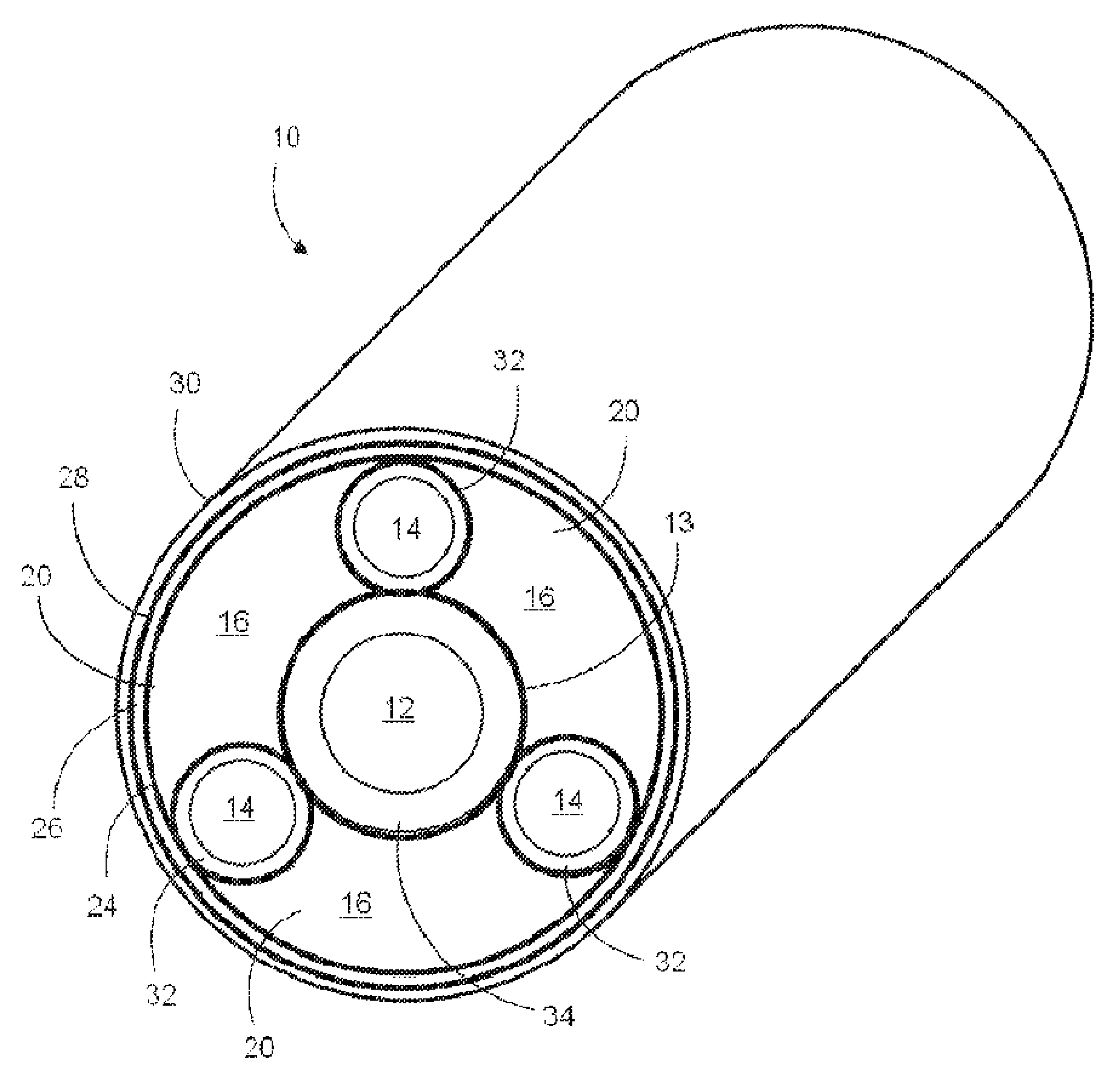
(57) **ABSTRACT**

A heater cable produces a substantially level voltage across its cross-section, providing a uniform and controllable thermal output along its length. The heater cable includes at least one center bus wire extending axially along a central axis of the heater cable, and at least one radial bus wire extending axially through the heating cable and positioned adjacent to the center bus wire. The heater cable further includes a thermally and electrically conductive interstitial material disposed around the at least one center bus wire and the at least one radial bus wire, and a jacket disposed about the interstitial material, the at least one center bus wire, and the at least one radial bus wire.

19 Claims, 8 Drawing Sheets



(51) **Int. Cl.**
H05B 3/12 (2006.01)
H01C 7/02 (2006.01)

(52) **U.S. Cl.**
CPC *H05B 2203/014* (2013.01); *H05B 2203/02* (2013.01); *H05B 2203/037* (2013.01); *H05B 2214/04* (2013.01)

(58) **Field of Classification Search**
CPC H05B 2203/02; H05B 2203/037; H05B 2203/019; H05B 2214/04; H01C 7/02
See application file for complete search history.

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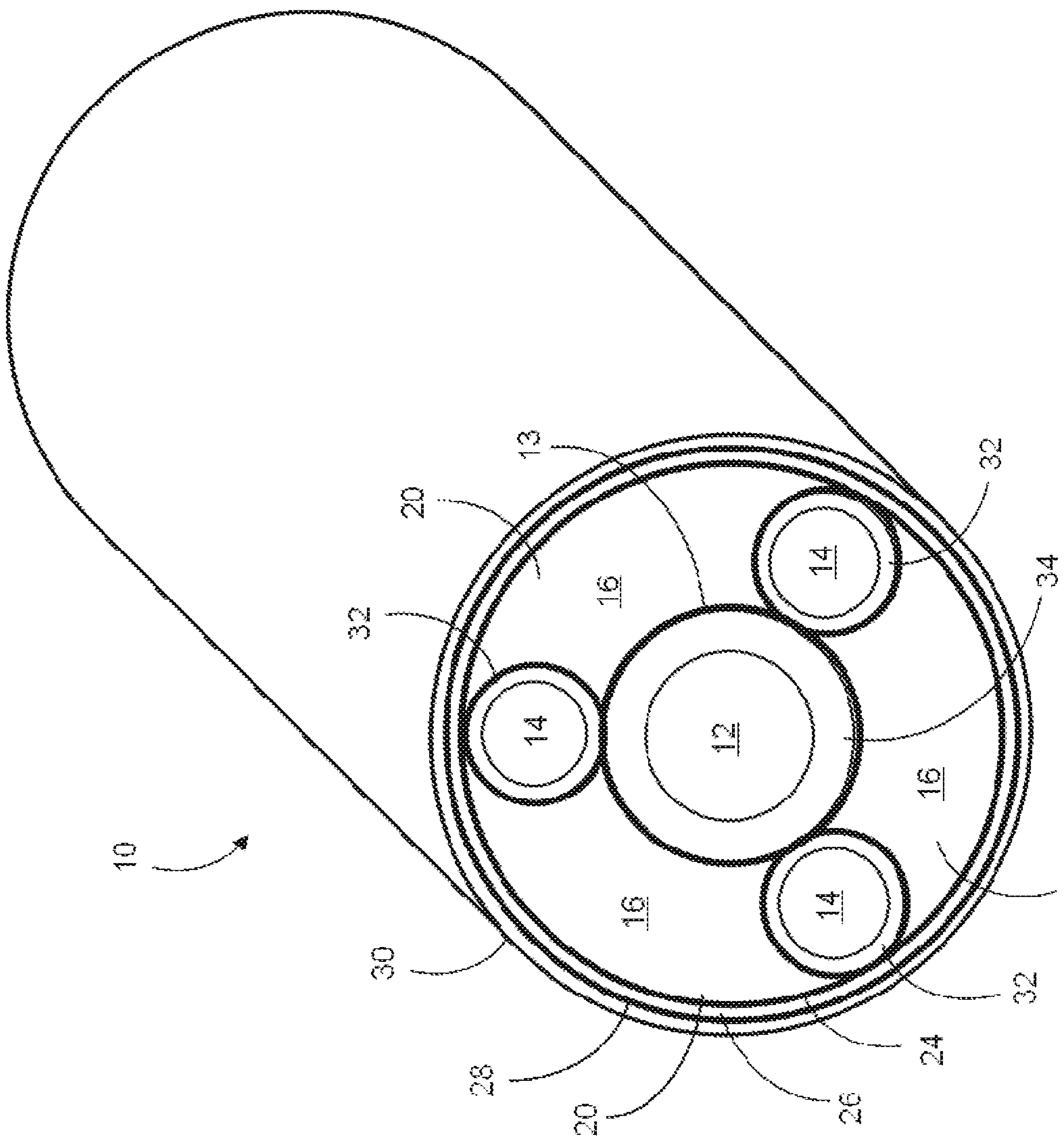


FIG. 1

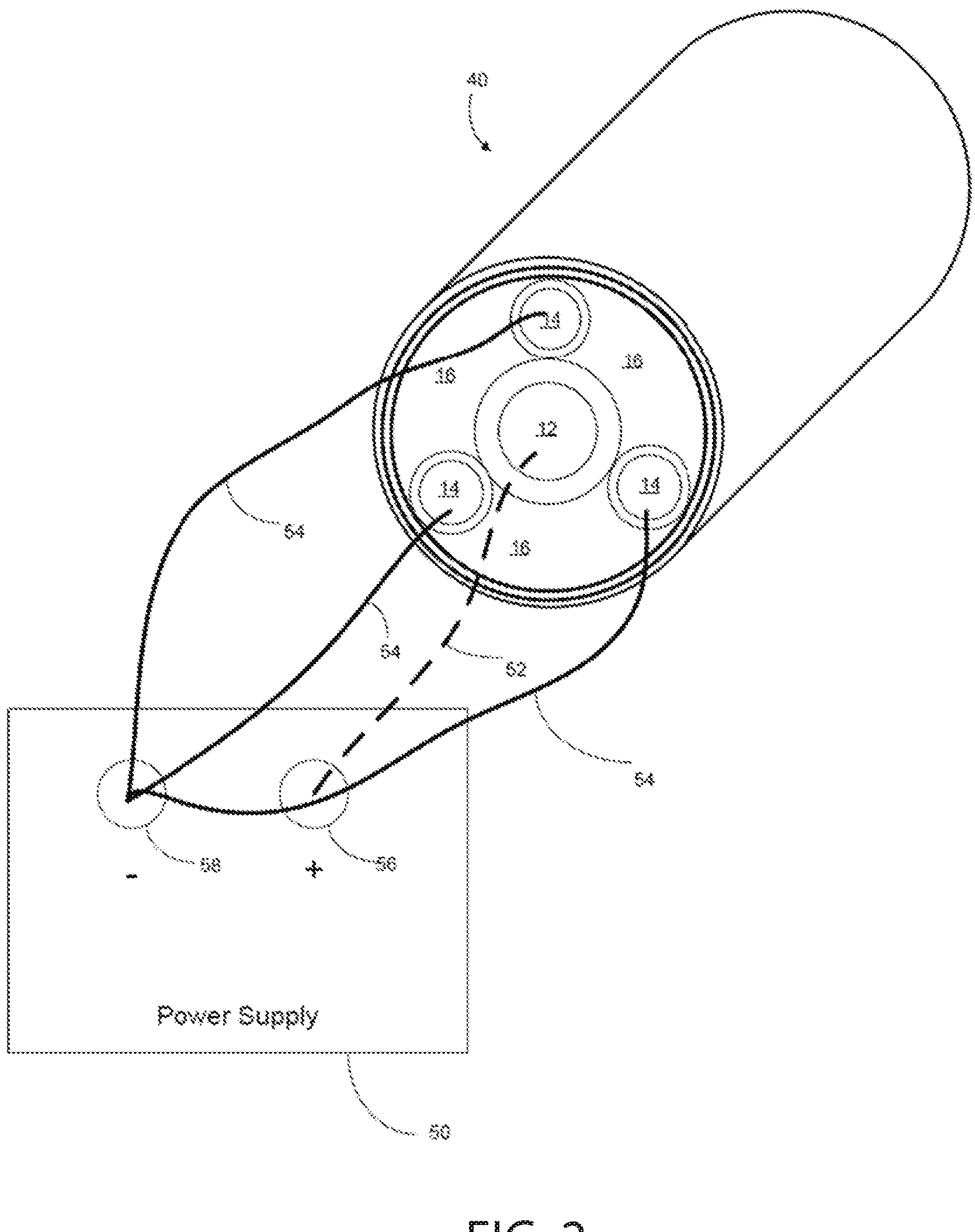
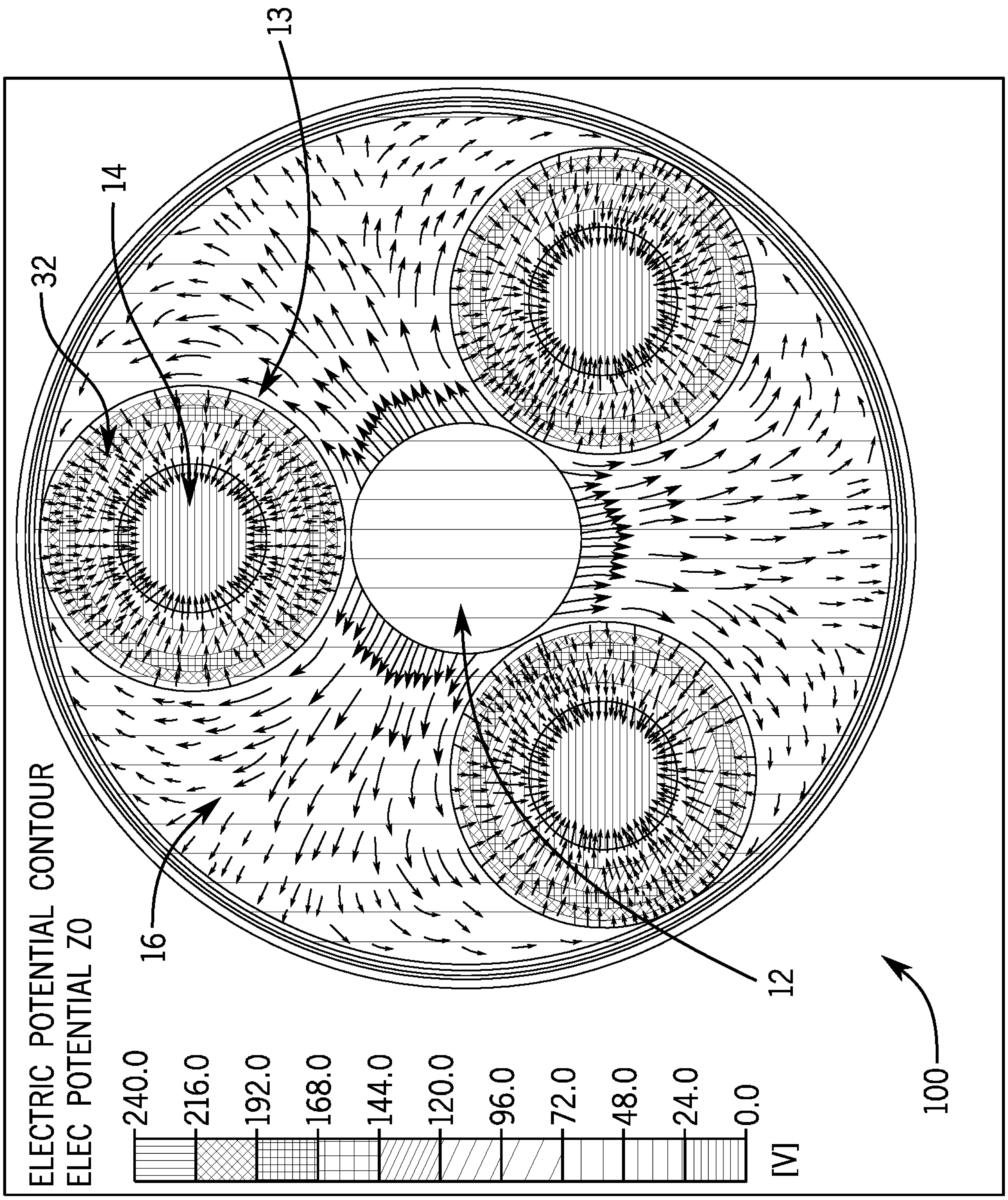


FIG. 2

FIG. 3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13
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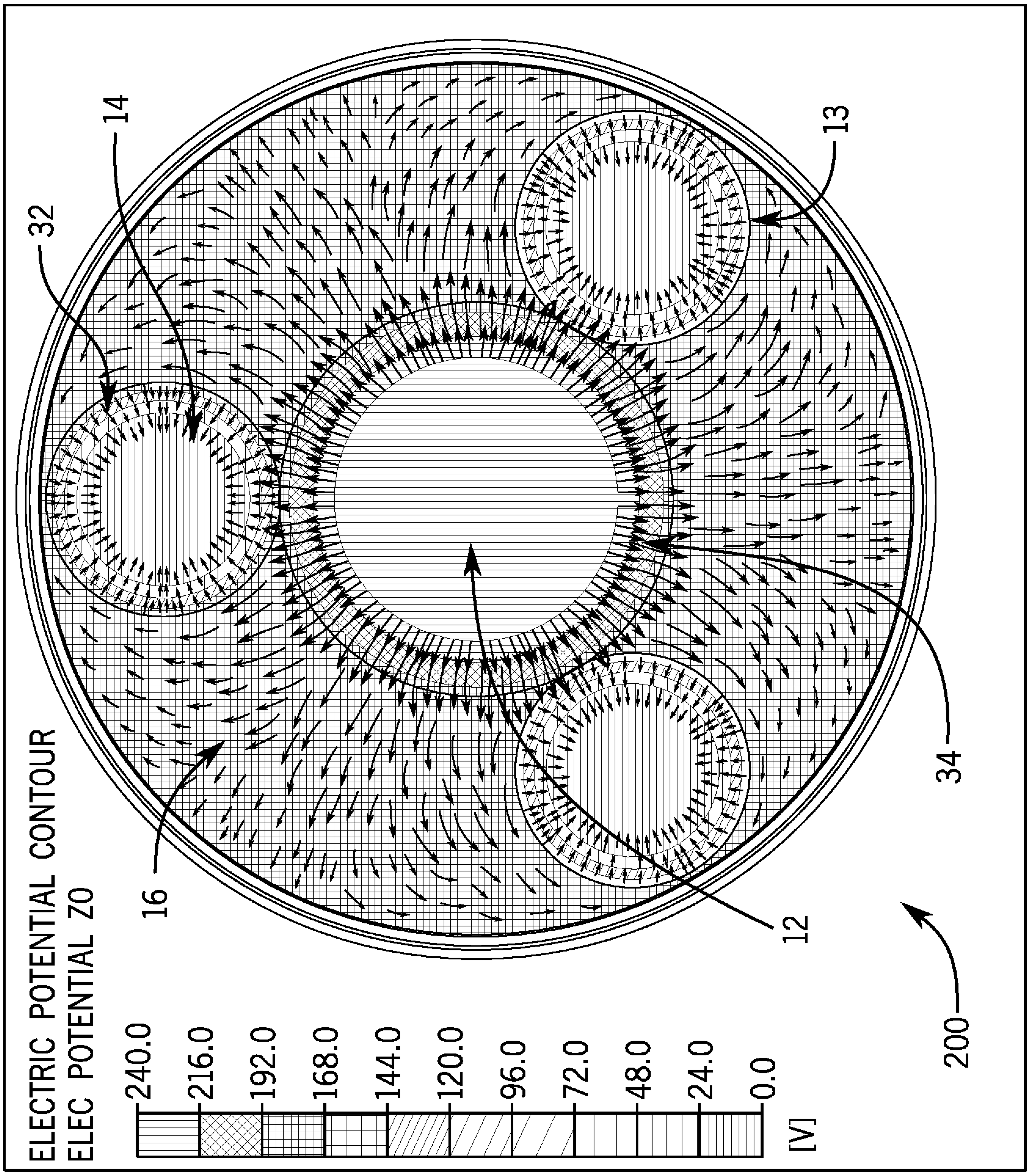
32
16
12
100

FIG. 4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14
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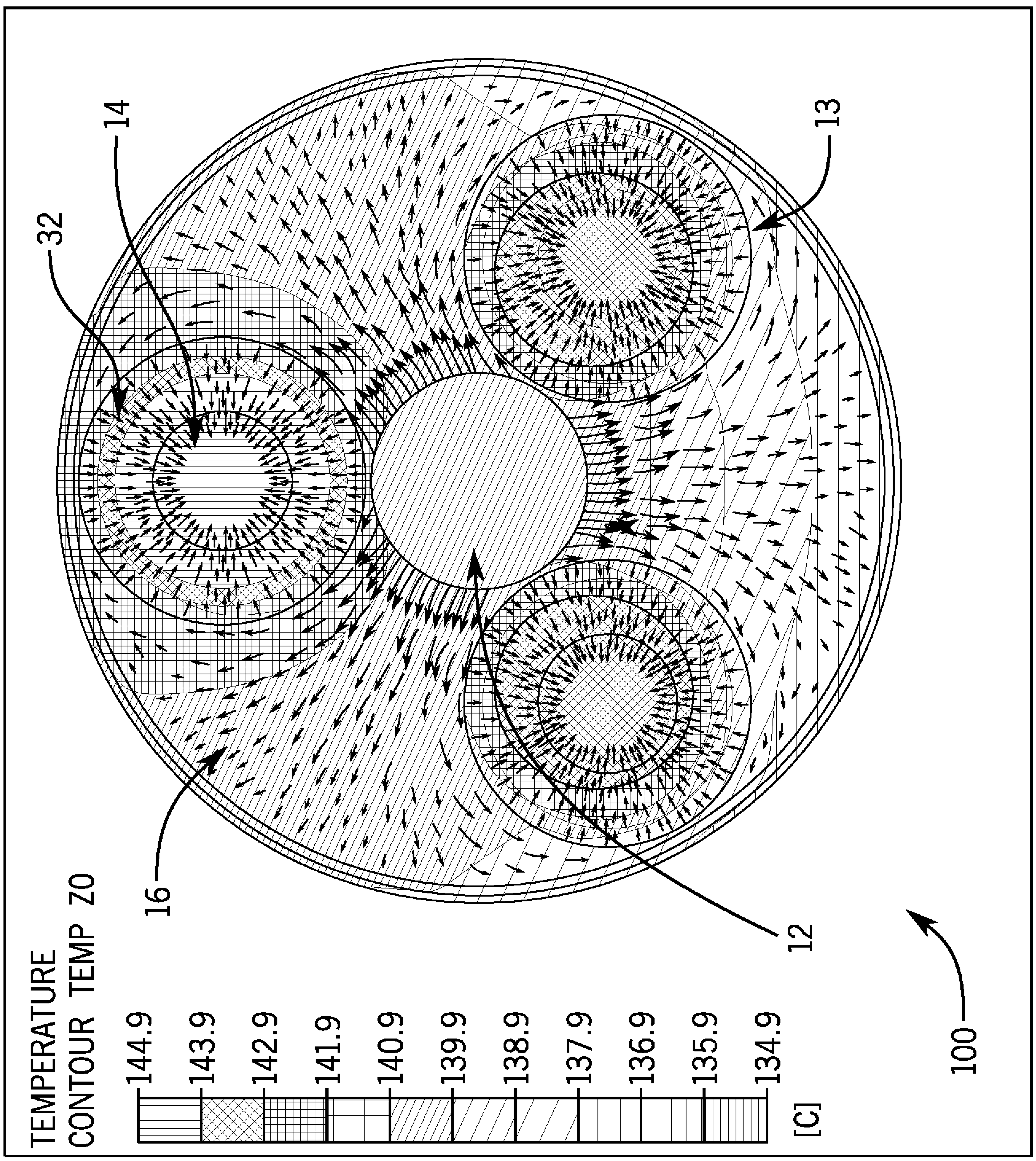
16
12
34
200

FIG. 5



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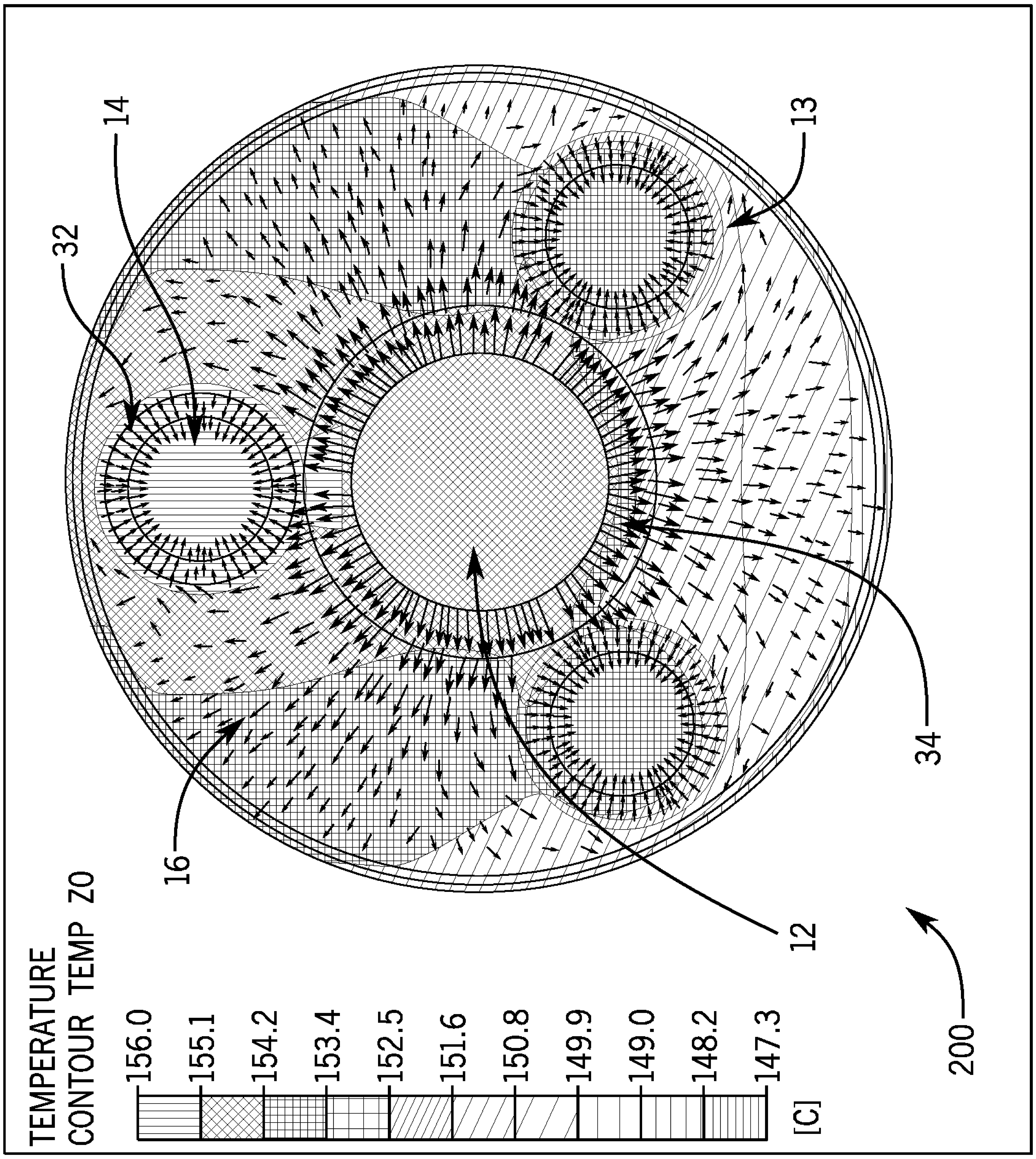
13
16
12
100

FIG. 6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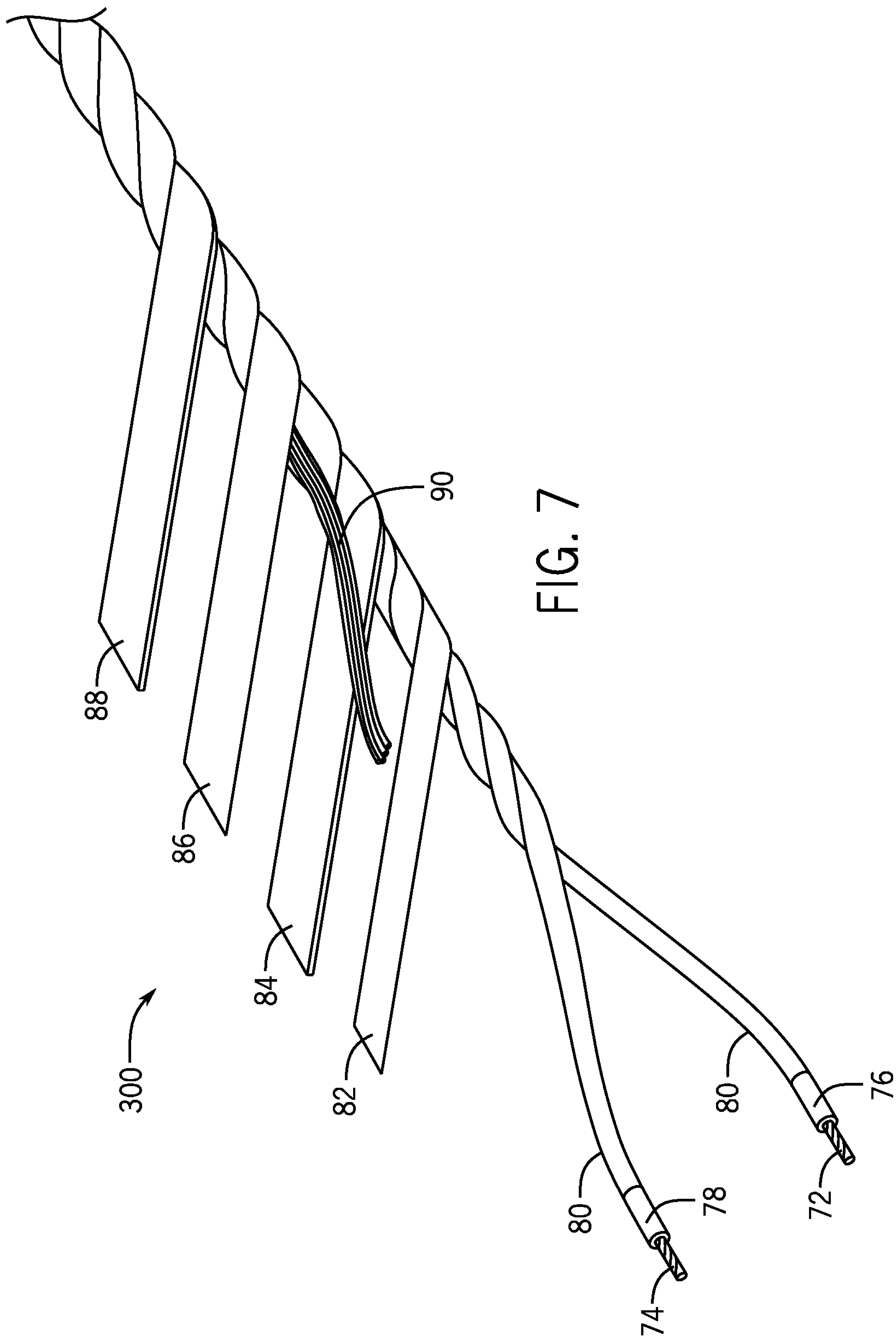

FIG. 7

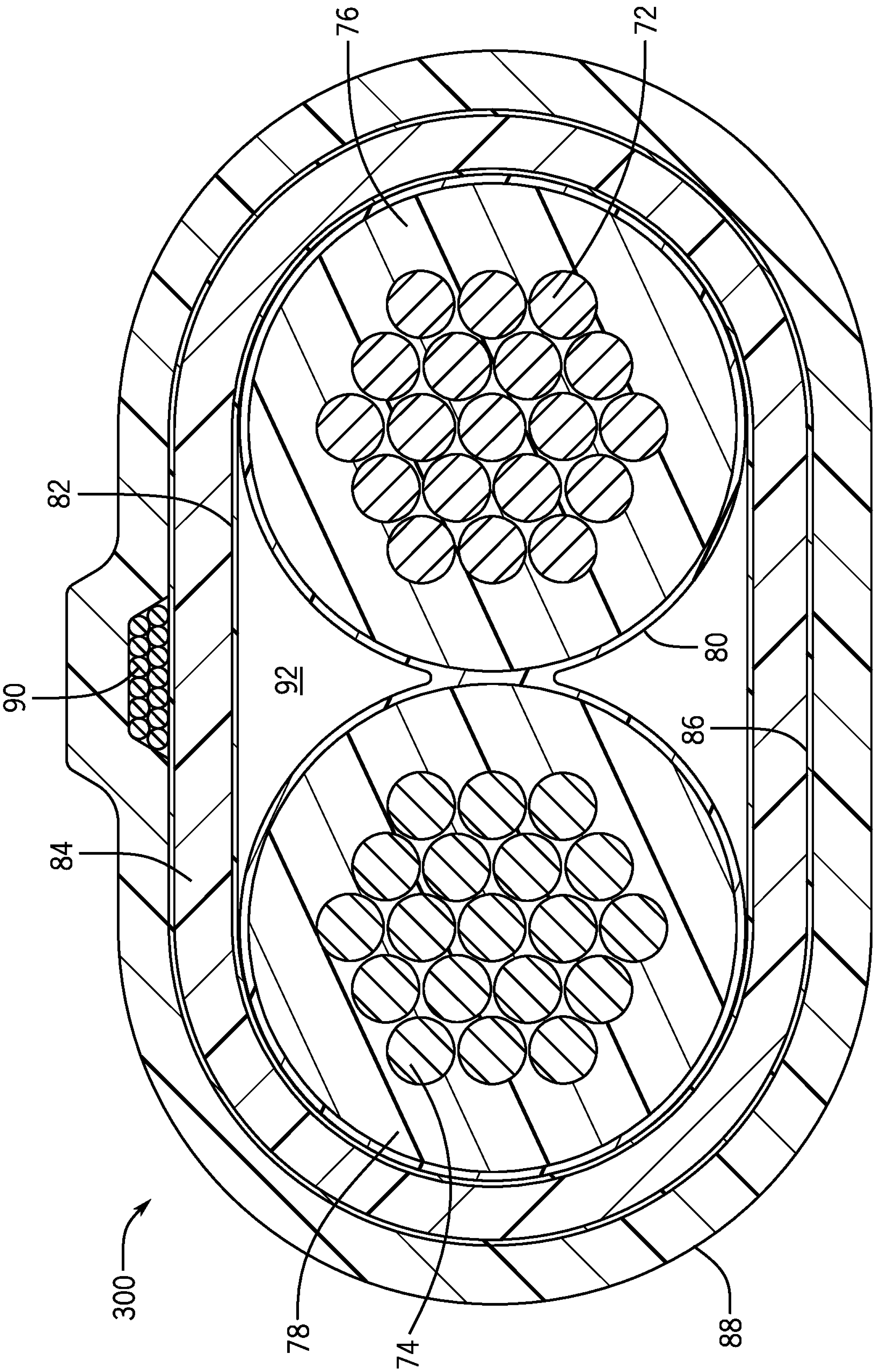

FIG. 8

VOLTAGE-LEVELING HEATER CABLE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/879,894, filed Oct. 9, 2015, under the same title, which is a non-provisional application claiming the benefit of U.S. Prov. Pat. App. Ser. No. 62/061,873, entitled "VOLTAGE-LEVELING HEATER CABLE" filed on Oct. 9, 2014.

FIELD OF THE INVENTION

The present invention generally relates to heater cables, and more specifically to self-regulating heater cables.

BACKGROUND OF THE INVENTION

Heater cables, such as self-regulating heater cables, tracing tapes, and other types, are cables configured to provide heat in applications requiring such heat. Heater cables offer the benefit of being field-configurable. For example, heater cables may be applied or installed as needed without the requirement that application-specific heating assemblies be custom-designed and manufactured, though heater cables may be designed for application-specific uses in some instances.

In some approaches, a heater cable operates by use of two or more bus wires having a high conductance coefficient (i.e., low resistance). The bus wires are coupled to differing voltage supply levels to create a voltage potential between the bus wires. A positive temperature coefficient (PTC) material can be situated between the bus wires and current is allowed to flow through the PTC material, thereby generating heat by resistive conversion of electrical energy into thermal energy. As the temperature of the PTC material increases, so does its resistance, thereby reducing the current therethrough and, therefore, the heat generated via resistive heating. The heater cable is thus self-regulating in terms of the amount of thermal energy (i.e., heat) output by the cable.

Heater cables can exhibit high temperature variations throughout the cable, both lengthwise along the length of the cable and across a cross-section of the cable. These high temperature variations may be caused by small high-active heating volumes (e.g., PTC material) within the heater cable that can create localized heating, as opposed to heat spread over a larger surface area or volume. Additionally, in certain configurations, heater cables can be relatively inflexible, or substantially rigid, thus making installation of the heater cable difficult. Further, heater cables are typically not configured to provide varying selective heat output levels by a user.

Though suitable for some applications, such heater cables may not meet the needs of all applications and/or settings. For example, a heater cable that reduces temperature gradients may be desirable in some instances. Further, a heater cable that is relatively flexible and rugged may be desirable in the same or other instances. Further still, a heater cable that is capable of producing varying selective heat output levels may be desirable in the same or other instances.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a cross-sectional diagram of a heater cable in accordance with various embodiments of the present disclosure;

FIG. **2** is a system view of a heater cable system in accordance with various embodiments of the present disclosure;

FIGS. **3** and **4** are cross-sectional diagrams illustrating electrical characteristics of the heater cable of FIG. **1** in accordance with various embodiments of the present disclosure;

FIGS. **5** and **6** are cross-sectional diagrams illustrating thermal characteristics of the heater cable of FIG. **1** in accordance with various embodiments of the present disclosure;

FIG. **7** is an exploded perspective view of another heater cable in accordance with another embodiment of the present disclosure; and

FIG. **8** is a cross-sectional diagram of the heater cable of FIG. **7**.

SUMMARY OF THE INVENTION

The present devices and systems provide a heater cable for generating heat when a voltage potential is applied. The heater cable can include at least one center bus wire extending axially along a central axis of the heater cable. The heater cable can further include at least one radial bus wire extending axially through the heating cable and positioned adjacent to the center bus wire. Further, the heater cable can additionally include a thermally and electrically conductive interstitial material disposed around the at least one center bus wire and the at least one radial bus wire; and a jacket disposed about the interstitial coating, the at least one center bus wire, and the at least one radial bus wire.

Additionally, a further heater cable is disclosed. The heater cable can include a center bus wire extending axially along a central axis of the heater cable; at least one radial bus wire extending axially through the heater cable and positioned adjacent to the center bus wire, the at least one radial bus wire being encapsulated with a PTC material; and a thermally and electrically conductive interstitial material disposed around the at least one center bus wire and the at least one radial bus wire, the interstitial material having an electrical resistance substantially less than an electrical resistance of the PTC material.

Furthermore, a heater cable system is disclosed. The heating system can include a power supply and a heater cable. The heater cable can include a center bus wire extending axially along a central axis of the heater cable; at least one radial bus wire extending axially through the heater cable and positioned adjacent to the center bus wire, the at least one radial bus wire being encapsulated with a PTC material having a greater resistance than the at least one radial bus wire and the center bus wire. The heating system further including a thermally and electrically conductive interstitial material disposed around the at least one center bus wire and the at least one radial bus wire; and the center bus wire electrically connected to a first voltage output of the power supply, and the at least one radial bus wire electrically connected to a second voltage output of the power supply, wherein the power supply generates a voltage potential between the center bus wire and the at least one radial bus wire.

DETAILED DESCRIPTION

The present invention overcomes the aforementioned drawbacks by providing in various embodiments a heater cable having a minimized operational temperature gradient. The minimized temperature gradient results in improved thermal equalization, thereby reducing maximum temperature generated at localized points of the heater cable and improving the lifespan of the heater cable. Further, in other embodiments, a heater cable is provided that provides the minimized temperature gradient while increasing flexibility and ruggedness compared to cables with similar dimensions and heating characteristics. In still other embodiments, the heater cable may be capable of selectively outputting varying levels of heat.

Referring now to the figures, FIG. **1** illustrates a cross-sectional view of a heater cable **10** in accordance with various embodiments. The heater cable **10** includes at least one center bus wire **12** and at least one or more radial bus wires **14**. The center bus wire **12** may reside within and along the center of the heater cable **10** or within the center of the radial bus wires **14** in certain embodiments. Although the center bus wire **12** is named as such, this does not imply that it necessarily resides within the center of the other radial bus wires **14** or the center of the heater cable **10** in all embodiments. Instead, in certain embodiments the center bus wire **12** may be intertwined or interleaved with the radial bus wires **14**. For example, the heater cable can have only two wires—a first wire that may be characterized as the center bus wire **12**, and a second wire that may be characterized as one of the radial bus wires **14**—and the first and second wires can be twisted or intertwined with each other along the center axis of the heater cable. In another embodiment, the radial bus wires **14** can be wrapped about the center bus wire **12** in a helical or spiral manner along all or part of the heater cable **10** length. The radial bus wires **14** can be helically wrapped around the center bus wire **12** at between 1 and 100 wraps per foot. Preferably, the radial bus wires **14** can be helically wrapped around the center bus wire **12** at between 20 and 80 wraps per foot. Most preferably, the radial bus wires **14** can be helically wrapped around the center bus wire **12** at between 30 and 50 wraps per foot. Additionally, the radial bus wires **14** can be helically wrapped around the center bus wire(s) **12** at a higher wrapping ratio or a lower wrapping ratio than those discussed above. In another embodiment, the radial bus wires **14** can be substantially parallel to, and not intentionally wrapped around, the center bus wire **12**. In other embodiments, the radial bus wires **14** can be positioned in an orientation that is not radial about the center bus wire **12**. Additionally, other wrapping patterns can be used.

In the embodiment illustrated in FIG. **1**, a single center bus wire **12** is shown surrounded by three radial bus wires **14**; however any number of center bus wire(s) **12** and/or radial bus wires **14** may be used. For example, and as will be made more apparent, a lesser or greater number of radial bus wires **14** may be used (e.g., one, two, three, four, five, and so forth). If a greater number of radial bus wires **14** are utilized, it may serve, in some embodiments, to further increase the thermal equalization effect described herein. However, for purposes of this disclosure, three radial bus wires **14** are illustrated and described, which teachings may be extrapolated or interpolated and resultantly applied to embodiments including an increased or decreased number of radial bus wires **14** (or center bus wire(s) **12**).

In at least one embodiment, the summed cross-sectional area of all of the radial bus wires **14** is equal to the cross-sectional area of the center bus wire **12**. However, this is not required in all embodiments and various ratios of cross-sectional areas may be utilized in various application settings. Additionally, in certain embodiments, the various radial bus wires **14** may have uniform or differing cross-sectional areas one from another. Further, the various radial bus wires **14** and/or center bus wire(s) **12** may have circular or non-circular cross-sectional shapes, and may even have differing cross-sectional shapes one from another (e.g., circular, oval, flat, ribbon, and so forth). These different shapes may be useful in certain application settings and are within the scope of the present disclosure.

With continued reference to FIG. **1**, an interstitial space **16** can exist between the center bus wire **12**, the radial bus wires **14** and an outer jacket **30** of the heater cable **10**. The interstitial space **16** can be a void within the heater cable **10**. In one embodiment, the interstitial space can contain an interstitial filler material **20**. The intersititial filler material **20** can partially or completely fill the interstitial space **16**. Additionally or alternatively, some or all of the exterior surface of the center bus wire **12** and/or the radial bus wires **14** can be coated with an interstitial coating **13**. The coating **13** can be applied to the bare conductor if any of the wires **12**, **14** are not encapsulated by the PTC materials **32**, **34** described below, or the coating **13** can be applied to the PTC materials **32**, **34**. The coating **13** can be applied to each wire **12**, **14** individually, or the coating **13** can be applied to an assembly of the center bus wire **12** and the radial bus wires **14**. For example, the radial bus wires **14** can be wrapped around the center bus wire **12** as described above, and then the coating **13** can be applied to the exposed exterior surfaces. In a further embodiment, an inner surface of any of the layers disposed around the assembly of wires **12**, **14** (e.g., the foil layer **24** or outer jacket **30**) can be coated with the interstitial coating **13**. Moreover, each or a sub-set of the center bus wires **12**, the radial bus wires **14** and the inner surface **22** of the outer jacket **30** can be coated with the interstitial filler material **20**.

In one embodiment, the interstitial filler material **20** and/or the interstitial coating **13** can be an electrically and thermally conductive carbon-based material, such as a carbon-based conductive ink. In some embodiments, this electrically and thermally conductive carbon based material can be a paracrystalline carbon coating, such as conductive carbon black. The carbon based material can, for example, have an electrical resistance of about 30 Ohms/square inch to about 230 Ohms per square inch per 25 micro-meters of thickness. In certain embodiments, the interstitial filler material **20** and/or the interstitial coating **13** can be initially made up of a slurry loaded with conductive particles (e.g., carbon black particles). The slurry may be applied to the center bus wire(s) **12** and/or radial bus wires **14**, and subsequently dried to remove the diluents post-application in order to form a flexible, solid material. In other embodiments, the interstitial filler material **20** and/or the interstitial coating **13** may include carbon or graphite bound within a matrix to be a flowable and curable polymer. Other examples of possible interstitial filler materials **20** and/or interstitial coatings **13** can include fluoropolymers, primary secondary amine (PSA) carbon black or other carbon blacks (including but not limited to conventional spherical shaped carbon black, acetylene black, amorphous black, channel black, furnace black, lamp black, thermal black, and single-wall or multi-wall carbon nanotubes), graphite (including but not limited to natural, synthetic, or nano), additives (for example, zinc oxide (ZnO) as an antioxidant, boron nitride (BN) as a processing aid, and others), non-carbon-based (e.g., silver-based or polymer-based) conductive inks, and/or mixtures of any of the above.

In some embodiments, including or not including the interstitial filler material **20**, the interstitial space **16** can be partially or completely filled with a filler material (not shown). Alternatively, in some examples, various voids can exist which can be filled with a filler material. Non-limiting examples of filler material can be thermally conductive grease, air and other non-volatile gasses, conductive carbon black, graphite, glass fiber, glass bead, metallic powder, metallic fiber, ceramic powder, ceramic fiber, and the like, and combinations of such suitable materials.

The center bus wire(s) **12**, the radial bus wires **14**, and the interstitial space **16** can form a core of the heater cable **10**. In one embodiment, the center bus wire(s) **12**, the radial bus wires **14**, and the interstitial space **16** are then wrapped in one or more outer jackets **30** to form a functional heater cable **10**. The one or more outer jackets **30** can be comprised of multiple layers. For example, in one embodiment, the jacket **30** includes a first metallic foil wrap **24** that is wrapped about the heater cable **10** core and is in electrical contact with the interstitial space **16** and/or the radial bus wires **14**. The metallic foil wrap **24** can be an aluminum foil wrap or other pliable, thermally conductive and/or electrically conductive wrap such as Nickel (Ni), Zinc (Zn) or their alloys laminated with polymeric films such as Kapton, Mylar, etc., which can improve tear resistance and mechanical integrity of the metallic foil wrap **24**. By using a metallic foil wrap **24** as the first layer, the metallic foil wrap **24** may aid in transferring heat and/or current and/or voltage about the heater cable **10**, thus improving thermal equalization.

A dielectric jacket layer **26** may reside outside of the first metallic foil wrap **24**, which may be formed of a thin polymer jacket. For example, the dielectric jacket layer may be formed from a polymer material such as a fluropolymer (for example, PFA, MFA, FEP, ETFE, ECTFE, PVDF, etc.), a polyolefin (for example HDPE, EAA, LDPE, LLDPE, etc.), a thermoplastic elastomer (for example, TPO, TPU, etc.) or a cross-linked rubber (for example EPDM, Nitrile, CPE, FKM, etc.). The dielectric jacket layer **26** can provide electrical insulation between the exterior of a heating cable **10**, and the conductive elements within the heater cable **10**. A second metallic foil wrap **28**, which may have the same or similar properties to the first metallic foil wrap **24**, may be provided outside of, and immediately adjacent to, an outer surface of the dielectric jacket layer **26**. In one example, the second metallic foil wrap **28** can be bonded to the outer surface of the dielectric jacket layer **26**. The second metallic foil wrap **28** can be bonded to the dielectric jacket layer using an adhesive. The second metallic foil wrap **28** may serve to help transfer heat around the circumference of the heater cable **10**.

Further, the second metallic foil wrap **28** may be in contact with a plurality of small metallic strands defining a drain wire (not shown). The drain wire can be distributed around the heater cable **10** (for example, outside and/or inside of the second metallic foil wrap **28**), which can provide an earth ground for the heater cable **10**. Lastly, an outer environmental jacket **30** may surround the second metallic foil wrap **28** and/or the drain wires, providing the heater cable **10** both electrical dielectric isolation and physical protection from its surrounding environment. The outer environmental jacket **30** may be made from a thin polymer jacket, or may be formed of rubber, Teflon, or another environmentally resilient material. In one embodiment, the outer environmental jacket **30** may be an extruded jacket, while in another embodiment the outer environmental jacket **30** may be a wrapped jacket, which can be wrapped around the heater cable **10**. In one example, the outer environmental jacket **30** can be helically or spiral wrapped around the heater cable **10**. Such a wrapped outer jacket may provide an articulated outer surface, which can result in increased flexibility for ease of installation and to better accommodate movement and handling of the heater cable **10** during installation and thereafter. The composition of the outer environmental jacket **30** can depend on the intended temperature rating (i.e., fluoropolymer jacket for high temperature rated heating cables, cross-linked polyolefin jacket for medium/low temperature rated heating cables, etc.). Flexibility may be further improved by helical or spiral wrapping of the radial bus wires **14** about the center bus wire **12**, which can also facilitate voltage leveling among the radial bus wires **14** and the central bus wire(s) **14** as described below.

Once assembled, the heater cable **10** may have a circular cross-section, as is shown in FIG. **1**. However, in other embodiments and in other application settings the heater cable **10** may take on a triangular cross-sectional shape due to the three radial bus wires **14** disposed about the center bus wire **12**. If more radial bus wires **14** are added, the cross-sectional shape may change (e.g., a square for four radial bus wires **14**, a pentagon for five radial bus wires **14**, and so forth). However, if the radial bus wires **14** are helically wrapped about the center bus wire **12** with relatively high frequency (e.g., more wraps per linear length), the cross-sectional shape may increasingly take a more circular shape. Many different cross-sectional shapes may be possible dependent upon the stacking pattern or wrapping pattern of the radial bus wires **14** and/or the center bus wire(s) **12**, the relative cross-sectional sizes of the radial bus wires **14** and/or center bus wire(s) **12**, and/or cable construction techniques utilized in the construction of the heater cable **10**. Various benefits of the differing cross-sectional shapes, numbers of radial bus wire(s) **14**, numbers of center bus wires **12**, wrapping patterns, volumes of interstitial space **16**, and cross-sectional volumes or shapes of various radial bus wires **14** and/or central bus wire(s) **12** may be realized and may be useful in varying application settings and are considered by this disclosure.

With continued reference to FIG. **1**, in one embodiment, the radial bus wires **14** may be encapsulated within a positive temperature coefficient (PTC) material **32**. In another embodiment, the center bus wire **12** may be encapsulated with the same, a similar, or a different PTC material **34** compared to the PTC material **32** of the radial bus wires **14**. The PTC material **32**, **34** encapsulations can be formed of various materials, including polymer-carbon compounds such as PFA, carbon black compounds, polyolefins (including, but not limited to polyethylene (PE), polypropylene (PP), polymethylpentene (PMP), polybutene (PB), polyolefin elastomers (POE), etc.), fluoropolymers (ECA from DuPont™, Teflon® from DuPont™, perfluoroalkoxy polymers (PFA, MFA), poly ethylenetetrafluoroethylene (ETFE), polyethylenechlorotrifluoroethylene (ECTFE), fluorinated ethylene-propylene (FEP), polyvinylidene fluoride (PVDF, homo and copolymer variations), Hyflon® from Solvay™ (e.g., P120X, 130X and 140X), polyvinylfluoride (PVF), polytetrafluoroethylene (PTFE), fluorocarbon or chlorotrifluoroethylenevinylidene fluoride (FKM), perfluorinated elastomer (FFKM)), and their mixtures.

Various applications of the PTC material **32**, **34** encapsulations are disclosed herein. In one embodiment, the radial bus wires **14** are encapsulated in PTC material **21** while the center bus wire **12** is not (e.g., is bare). In an alternate embodiment, both the radial bus wires **14** and the center bus wire **12** are encapsulated in their respective PTC materials **32**, **34**. In a further embodiment, the center bus wire **12** is encapsulated with PTC material **34** while all or some of the radial bus wires **14** are not (e.g., are bare). Alternatively, other variations are possible, such as coating only some of the radial bus wires **14**. Further, the radial bus wires **14** and the center bus wire(s) **12** can have the same thickness of PTC material **32**, **34** applied. Alternatively, the radial bus wires **14** can be encapsulated with one thickness of PTC material **32** and the central bus wire(s) **12** can be encapsulated with a second thickness of PTC material **34** which may be thicker or thinner than the first PTC material **32**. Further, the central bus wire(s) **12** and/or the radial bus wires **14** can have varying thicknesses of PTC material **32**, **34** along a linear axis of the cable **10** to provide different heating characteristics along the length of the heating cable **10**.

The PTC material **32**, **34** encapsulations can be high-active heating elements and can operate as heating elements within the heater cable **10**. The PTC material **32**, **34** encapsulations can generate heat, as the PTC material **32**, **34** can have a substantially higher resistance than the conductors of the center bus wire **12** and the radial bus wires **14** (which have negligible resistances), and the interstitial filler material **20** (which can have a negligible to extremely low resistance). Resistive heating is generated by power dissipation. Power (P) is generally defined as P=I^2×R, where "I" represents current and "R" represents resistance. Due to the substantially higher resistance of the PTC material **32**, **34**, substantially more power is dissipated by the PTC material **32**, **34** than the interstitial filler material **20**, where current is constant; accordingly, more heat is produced by the PTC materials **32**, **34** than from the interstitial filler material **20**. The heat generated by the PTC material **32**, **34** is then transferred toward the outer jacket **30** of the heater cable **10**, and subsequently to the exterior of the heater cable **10**. The heat generated by the PTC material **32**, **34** can then be transferred to materials or structures which are in close proximity, or in contact with the heater cable **10**. Where the heater cable **10** is not in close proximity or in contact with a material or structure, the heat can be dissipated into the surrounding environment. Heat transfer from the PTC material **32**, **34** can be affected, in some instances, by the highly thermally conductive characteristic of the interstitial filler material **20**. For example, the interstitial filler material **20** can affect the temperature rating and/or power output of the heater cable **10**. In one example, the interstitial filler material **20** can increase the temperature rating and/or the power output of the heater cable by providing even current distribution throughout the heater cable **10**. Further, the interstitial filler material **20** can increase the temperature rating of the heater cable **10** by allowing for even heat distribution, thereby reducing the possibility of hot spots within the heater cable **10**.

The PTC material **32**, can limit the current passed through the PTC material **32**, **34** based on the temperature of the PTC material **32**, **34**. The PTC material **32**, **34** has a positive temperature coefficient, meaning the material will increase its electrical resistance as its temperature increases. As the resistance of the PTC material **32**, **34** increases, the current thereby decreases, and the heat locally generated by the flow of current thereby decreases as well. Thus, the heater cable **10** can be self-regulating in that its resistance varies with temperature. For example, portions of the heater cable **10** will have low resistance where the temperature is below a designed heater cable **10** set-point, thereby leading to higher current between the radial bus wires **14** and the central bus wire(s) **12**, and, greater heat generation. Conversely, portions of the heater cable **10** can have higher resistance where the temperature is above the designed heater cable **10** set-point, thereby leading to lower current between the radial bus wires **14** and the central bus wire(s) **12**, and, lower heat generation. When the heater cable **10** temperature reaches a designed set-point, the resistance of the PTC material **32**, **34** can increase and thereby reduce heat generation.

In this manner, heat is regulated by the PTC material **32**, **34** along the length of the heater cable **10** and across the cross-section of the heater cable **10**. Further, the above implementation allows for the heater cable **10** to achieve the desired temperature set points along the entire length and cross-section. Further, the heater cable **10** can be designed to allow for multiple temperature set points along its length. In one embodiment, where the radial bus wires **14** are helically or spirally wrapped about the center bus wire(s) **12**, virtually equivalent self-leveling of the longitudinal currents in the plurality of radial bus wires **14** can be achieved. For example, in most application settings, due to the helical/spiral wrapping, equal portions of each radial bus wire **14** will reside closest to a heat sink (e.g., a pipe, structure, etc.), thereby effectively equalizing the current load for each individual radial bus wire **14** with respect to the other radial bus wires **14**. Further, the helical/spiral wrapping in conjunction with the interstitial coating (or with the interstitial filler material **20** in contact with the wires **12**, **14**) can aid in voltage leveling by increasing the potential electrical paths for the current to flow between the center bus wire(s) **12** and the radial bus wires **14** of the heater cable **10**. This increase in electrical paths can increase the active volume of the PTC material **32**, **34** (i.e. increase the surface area of current flow through the PTC material **32**, **34**) thereby lowering the overall temperature of the PTC material **32**, **34**, and reducing localized heating.

The desired temperature set points discussed above can be set using multiple methods. For example, the material type and/or thickness of the PTC material **32**, **34** encapsulations can be selected to provide the desired temperature set point. Further, the thickness of the PTC material **32**, **34** encapsulations can be varied at different positions along the length of the heating cable **10** to provide multiple temperature setpoints along the length of the heating cable **10**. Alternatively, the type and/or density of the interstitial filler material **20** in the interstitial space **16** can be varied to provide the desired temperature set point. Furthermore, a voltage applied to the center bus wire(s) **14** can be varied to provide the desired temperature set point. While each of the above methods for setting the desired temperature set point are discussed individually, each of the above examples can be applied individually or in various combinations to provide the desired temperature set point. Additionally, the desired temperature set point can be accomplished by using various combinations of conductor sizes for the radial bus wires **14** and the center bus wire(s) **12** (e.g., 14 AWG, 16 AWG, 20 AWG, etc.). Additionally, various constructions (e.g., number of strands in the conductor) of the conductors can be used for the radial bus wires **14** and the center bus wire(s) **12** to achieve the desired temperature set point.

In one embodiment, a voltage potential is developed between the center bus wire(s) **12** and the radial bus wires **14**. For example, the center bus wire(s) **12** may be coupled to a first output of a power supply **50** (FIG. **2**) while the radial bus wires **14** may be coupled in parallel to a second output of the power supply **50**. When a voltage potential exists between the first output of the power supply and the second output of the power supply, that voltage potential is present between the center bus wire(s) **12** and radial bus wires **14**, respectively. For example, the center bus wire(s) **12** may be coupled to a high voltage output while the radial bus wires **14** may be coupled to a neutral voltage output, or vise versa. The high voltage output can be an AC voltage or a DC voltage. Additionally, other configurations are possible, including three-phase AC configurations involving different voltage phases applied to multiple center bus wire(s) **12**, and/or radial bus wires **14**.

Other embodiments may include selectively coupling and/or decoupling various radial bus wires **14** to/from the respective voltage source (e.g. power supply), or coupling various radial bus wires **14** to multiple voltage potentials. In this manner, in a first configuration, the radial bus wires **14** may all be electrically in parallel to one another (either galvanically or by virtue of having a same voltage potential applied thereto). In such a configuration, each of the radial bus wires **14** may have the same voltage potential relative to the center bus wire **12**, which as illustrated below, can have the effect of distributing current and heat more evenly throughout the heater cable **10**. In another configuration, one or more of the radial bus wires **14** can be disconnected from the voltage potential source so as to reduce the total amount of heat generated within the heater cable **10**. This can allow installers or users of the heater cable **10** to select a desired discrete heat output level by selecting the number of radial bus wires **14** connected to the power source. The selection may be made at the time of installation.

Alternatively, the number of radial bus wires **14** connected to the power source may be adjusted after installation, and can be continually modified to meet the dynamic needs of a specific application setting. For example, during summer months, minimal heat may be needed. Accordingly, only one radial bus wire **14** may need to be connected to the power source **50** to provide the required level of heating. However, during the winter months, maximum heat may be needed, requiring all of the radial bus wires **14** to be connected to the power source **50**. In yet another configuration, one or more of the radial bus wires **14** may be connected to the same voltage potential as the center bus wire(s) **12** or another voltage potential all together. By changing the magnitude of the voltage potentials between the radial bus wires **14** and the center bus wire **12**, various current and temperature gradients can be achieved, and the overall heat output of the heater cable **10** can be affected, which results may be desirable in some application settings.

In various embodiment as described herein, by distributing a voltage potential to a plurality of radial bus wires **14** that are physically separated from one another, current can flow from the center bus wire **12** to the plurality of radial bus wires **14** in a multitude of varying directions creating a wider and more evenly distributed current field through the interstitial space **16**. Additionally, the interstitial coating **13** and/or the interstitial filler material **20** can further allow for wider and more evenly distributed current field through the interstitial space **16**. This allows for a more uniform heat generation pattern across the entirety of the PTC encapsulation **32**, **34** of the radial bus wires **14** or the center bus wire **12**. Additionally, by distributing the radial bus wires **14** across the cross-section of the heater cable **10**, the physical locations of the source of heat generation are thereby spread throughout the cross-section of the heater cable **10**. This can result in a reduced temperature gradient across the heater cable **10**, resulting in better thermal equalization along the length of the heater cable **10**.

Further, by placing the radial bus wires **14** around the center bus wire(s) **12**, the heater elements can be physically closer to the outside diameter of the heater cable **10**. This can result in more efficient heat transfer out of the heater cable **10** and into the surrounding environment. Moreover, by using a heating cable **10** with a plurality of radial bus wires **14**, the radial bus wire **14** surface area is increased, thereby increasing the amount of PTC material **32**, **34** that can be used within the heater cable **10**. This can spread the heat generation over a larger amount of surface area and across a larger volume of the heating cable **10**, which can reduce the opportunity for the formation of hot spots. These effects together serve to maximize thermal equalization within the heater cable **10**, resulting in more consistent heating along the entire length of the heating cable **10**. This may improve the lifespan of the heater cable **10** and reduce the potential for premature failure due to degradation. Further, these effects may improve the unconditional sheath temperature classification of the heater cable **10** as specified by European norm EN60079-30-1.

FIG. **2** illustrates a possible embodiment of a heating cable system. The heating cable **40** can be the same configuration as heater cable **10** shown in FIG. **1** and can include a center bus wire **12**, a plurality of radial bus wires **14**, and interstitial filler material **20**. Alternatively, heater cable **10** can have multiple configurations as discussed above. Heater cable **40**, can be coupled to a power supply **50**, via power leads **52**, **54**. The power supply **50** can be an AC power supply or a DC power supply. Additionally, while the power supply **50** is shown with only a positive terminal **56** and a negative terminal **58**, it should be understood that the power supply **50** in FIG. **2** is for illustrative purposes only and can include multiple configurations. For example, the power supply **50** can have multiple output ports, capable of outputting multiple voltage levels. Further, the power supply **50** can be a multi-phase AC power supply. In some embodiments, the power supply **50** can be a simple power source, i.e. a connection to a utility provided power.

Power lead **52** can be coupled to the positive output terminal **56** of the power supply **50**, and to the center bus wire **12** to provide a positive voltage potential to center bus wire **12**. Alternatively, power lead **52** can be coupled to the negative output terminal **58** of the power supply **50** to provide a negative (i.e. lower potential or ground) voltage potential to center bus wire **12**. Additionally, the at least one radial bus wires **14** can be coupled to the negative output terminal **58** of the power supply **50** via power lead **54** to provide a negative (i.e. lower potential or ground) voltage potential to the at least one radial bus wires **14**. Alternatively, the at least one radial bus wires **14** can be coupled to the positive output terminal **58** of the power supply **50** via power lead(s) **54** to provide a positive voltage potential to the at least one radial bus wires **14**. In some embodiments, each of the at least one radial bus wires **14** can be connected to individual power supply **50** outputs. As discussed above, this can allow a user to apply a specific voltage to each of the radial bus wires **14** to allow for specific temperature set-points to be achieved. The system of FIG. **2** represents one possible embodiment of a heating cable system, multiple further embodiments, such as those discussed above, can further be implemented as required for a given application.

Turning now to FIGS. **3** and **4**, a voltage potential distribution and a current distribution (shown by black vector arrows) within a heater cable are illustrated in accordance with various embodiments. FIG. **3** shows an embodiment of a heater cable **100** wherein the radial bus wires **12** are encapsulated with PTC material **32** while the center bus wire **12** is bare (i.e., not covered with PTC material). As can be seen, the center bus wire **12** and the interstitial space **16** share an identical or near identical voltage potential (i.e., high voltage) and the radial bus wires **14** share an identical voltage potential (i.e., low) with each other. The interstitial space **16** can include interstitial filler material **20** as discussed above. A voltage drop occurs across the PTC material **32**. Because the voltage potential encountered by nearly the entirety of the circumference of the PTC material **32** is identical (by virtue of the highly conductive coating **13**), the voltage drop across the PTC encapsulation **32** is substantially uniform, and thus the current flow therethrough is substantially uniform, resulting in substantially uniform heat generation. It should be noted that in certain embodiments, a first metallic foil wrap **24** (discussed above) can be in direct contact with all or portions of the interstitial space **16** and can further aid in electrical distribution of current within and across portions of the interstitial space **16**.

FIG. **4** illustrates a slightly different embodiment where both the radial bus wires **14** and the center bus wire **12** are encapsulated in PTC material **32**, **34** in heater cable **200**. A first voltage drop occurs across the PTC material **34** around the center bus wire **12** with a corresponding first heat generation effect. The interstitial space **16** then has a reduced voltage potential, but is still uniform throughout. This can be the result of the interstitial filler material **20** within the interstitial space **16**. A second voltage drop occurs across the PTC material **32** around the radial bus wires **14** corresponding to a second heat generation effect. Because the interstitial space **16** has a uniform voltage potential due to the interstitial filler material **20**, the current through both PTC materials **32**, **34** is relatively uniform throughout their respective circumferences, thereby spreading heat generation evenly throughout the entirety of the encapsulations of PTC materials **32**, **34**.

Turning now to FIGS. **5** and **6**, heat distribution profiles are illustrated in accordance with various embodiments described herein. The heater cable **100** shown in FIG. **5** is identical to that of FIG. **3**, whereas the heater cable **200** shown in FIG. **6** is identical to that of FIG. **4**. The illustrative heat distribution profiles are shown assuming a thermal coupling on the lower edge to a heat sink (e.g., pipe, structure, or other material receiving heat, correlated to the bottom of the page). As can be seen in both FIGS. **5** and **6**, the heat generated by the PTC material **32**, **34** is spread relatively evenly across the entire cross-section of the heater cable **100**, **200**. For example, as is shown in FIGS. **5** and **6**, a temperature differential of less than 10° C. is seen across the entire cross section heater cable **100**, **200**. Within the heater cable **100**, **200** cores, temperature differentials of less than 7° C. can be seen. These figures therefore illustrate effective thermal equalization across the entire heater cable **100**, **200** cross-section.

FIGS. **7** and **8** illustrate another embodiment of a heater cable **300** having the properties described above. A first bus wire **72**, like the center bus wire **12** of FIG. **1**, can have a PTC material cover **76** encapsulating the first bus wire **72**, as described above with respect to the PTC material **34**. A second bus wire **74**, like one of the radial bus wires **14** of FIG. **1**, can also have a PTC material cover **78** encapsulating the second bus wire **74** as described above with respect to the PTC material **32**. Thus, the PTC materials and the thicknesses of the covers **76**, **78**, can be the same or different. The bus wires **72**, **74** themselves can be solid-core or multi-stranded, as illustrated, and can be the same or different diameters. The bus wires **72**, **74** can be twisted together (i.e., around the center axis of the cable **300**), and can form a twisted pair cable that may reduce electromagnetic interference and improve efficiency of current and/or heat transfer from the first bus wire **72** to the second bus wire **74** through the covers **76**, **78**.

One or both of the bus wires **72**, **74** can be coated with a conductive coating **80**, such as conductive ink or another material as described above with respect to the interstitial coating **13** of FIG. **1**. The coating **80** can be applied to the bare wire, or to the external surfaces of the covers **76**, **78**. The coating **80** can be applied around the entire circumference (i.e., on the entire surface area) of the external surface, or the coating **80** can be applied to only a portion of the external surface. Each bus wire **72**, **74** can be separately coated before the bus wires **72**, **74** are twisted together. In such embodiments, the bus wires **72**, **74** can be twisted together before the coating **80** has dried or otherwise hardened, which can allow the coatings **80** of the separate wires to flow or fuse together, or otherwise conglomerate, at the point of contact between the bus wires **72**, **74**. This can create a thicker portion of the coating **80** at the point of contact, as shown in FIG. **8**. Alternatively, the bus wires **72**, **74** can be twisted together after the coatings **80** have dried or hardened. Additionally or alternatively, the bus wires **72**, **74** can be twisted together and then coated with the coating **80**. In such embodiments, the covers **76**, **78** may contact each other beneath the coating **80**. The coating **80** can be the same thickness or a different thickness on each of the bus wires **72**, **74**.

A jacket can be formed from several layers, similar to the construction described above with respect to FIG. **1**. An inner conductive layer **82** can be a metallic foil or other suitable conductive film that is wrapped (as shown) or otherwise disposed over the twisted pair of bus wires **72**, **74**. The inner conductive layer **82** may contact the coating **80** and facilitate uniform distribution of the current during current transfer. The wrapping of the inner conductive layer **82** can define the interstitial spaces **92** between the first bus wire **72**, the second bus wire **74**, and the inner conductive layer **82**. The interstitial spaces **92** can be voids or can be filled with an interstitial filler as described above. The coating **80** may further be applied to an internal surface of the inner conductive layer **82**.

A dielectric layer **84** can be wrapped (as shown) or otherwise disposed over the inner conductive layer **82**. Alternatively, the inner conductive layer **82** can be omitted, and the coating **80** can be applied to an internal surface of the dielectric layer **84**. The dielectric layer can be an electrically insulating material as described above with respect to the dielectric jacket layer **26** of FIG. **1**. A second conductive layer **86** can be wrapped or otherwise disposed over the dielectric layer **84**. As described above with respect to the second metallic wrap **28**, the second conductive layer **86** can be a metallic foil or another suitable conductive material. Alternatively, the second conductive layer **86** can be omitted, and the coating **80** can be applied to an external surface of the dielectric layer **84**. The second conductive layer **86** can be in electrical contact with one or more drain wires **90** serving as the ground wire of the heater cable **300**. An outer jacket layer **88** can be wrapped or otherwise disposed around the other layers of the jacket. The outer jacket layer **88** can have the properties of the outer environmental jacket **30** of FIG. **1**.

As illustrated in FIG. **8**, the heater cable **300** can have a generally elongated cross-sectional shape. A heater cable **300** having a generally elongated cross-sections shape can have one or more flat surfaces, which can be useful where the heater cable **300** is coupled to another substantially flat surface to be heated. Additionally, the heater cable **300** can also be configured to have other cross-sectional shapes, such as a round shape, an oval shape, or other shape required for a given application. In one embodiment, a filling material (not shown) can be used to provide structural support within the heater cable **300** to shape the cable into a alternate shape, such as a rounded shape. In one example, the filler material can be inserted into the interstitial space **92** to modify the shape of the heater cable **300**. In an alternate embodiment, the filling material can be inserted between one or more layers of the jacket. For example, the filling material can be inserted between inner conductive layer **82** and the internal surface of the dielectric layer **84**, between the dielectric layer **84** and the second conductive layer **86**, between the second conductive layer **86** and the outer jacket layer **88**, or any combination thereof. Further, the filler material can be placed between any of the layers discussed above, as well as in the interstitial space **92**.

In one embodiment, the filler material can be an electrically and/or thermally conductive material, an electronically and/or thermally non-conductive material, or a combination thereof. Generally, the filling material is be selected based on requirements of the heater cable **300** application. For example, electrical conductivity, thermal conductivity, temperature rating, thermal resistance, chemical resistance, etc., are all factors that can be used when selecting the filling material. In one embodiment, similar materials to the described in relation to the interstitial filler material **20** discussed above can be used as the filling material. For example, fluoropolymers, primary secondary amine (PSA) carbon black or other carbon blacks (including but not limited to conventional spherical shaped carbon black, acetylene black, amorphous black, channel black, furnace black, lamp black, thermal black, and single-wall or multi-wall carbon nanotubes), graphite (including but not limited to natural, synthetic, or nano), additives (for example, zinc oxide (ZnO) as an antioxidant, boron nitride (BN) as a processing aid, and others), non-carbon-based (e.g., silver-based or polymer-based) conductive inks, and/or mixtures of any of the above, are suitable materials for use as the filling material. Other filling materials such as, glass fiber, glass bead, metallic powder, metallic fiber, ceramic powder, ceramic fiber, and the like, and combinations of such suitable materials can also be used as the filling material. In one embodiment, the same filling material can be used throughout the heater cable **300**. Alternatively, different filling material types can be used throughout the heater cable **300**. For example, a first filling material type can be used in the interstitial space **92**, and a second filling material type can be used between the layers **82**, **84**, **86**, **88**. Further, different filling material types can be used between each of the layers **82**, **84**, **86**, **88** as well as the interstitial space **92**.

So configured, a heater cable is described capable of having improved thermal equalization characteristics according to various embodiments, such as those described above. Additionally, the design of the heater cable in various embodiments allows for flexibility and ruggedness while maintaining a maximized thermal equalization, which, in particular, is a new and useful result. Further still, the heater cable in accordance with various embodiments is capable of producing varying selective heat output levels by selectively activating and deactivating various bus wires therein.

The present invention has been described in terms of one or more preferred embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated (e.g., methods of manufacturing, product by process, and so forth), are possible and within the scope of the invention.

We claim:

1. A heater cable comprising:

a center bus wire extending axially along the heater cable;

a first radial bus wire extending axially along the heater cable and positioned adjacent to the center bus wire;

a first cover encapsulating the first radial bus wire, the first cover comprising a first positive temperature coefficient (PTC) material;

an electrically conductive coating disposed on the first cover, the coating forming one or more electrical paths for an electric current carried by the center bus wire to be conducted to the first radial bus wire through the first cover with a substantially uniform distribution of the electric current within the first PTC material of the first cover; and

a jacket disposed over and containing the center bus wire and the first cover, the jacket comprising a metallic foil layer in electrical contact with the coating;

the first PTC material having a substantially higher resistance than the center bus wire, the first radial bus wire, and the coating.

2. The heater cable of claim **1**, further comprising:

a second radial bus wire extending axially through the heating cable and positioned adjacent to the center bus wire;

a second cover encapsulating the second radial bus wire, the second cover comprising the first PTC material;

a third radial bus wire extending axially through the heating cable and positioned adjacent to the center bus wire, the first, second, and third radial bus wires being uniformly spaced apart from each other in a radial arrangement around the center bus wire; and

a third cover encapsulating the third radial bus wire, the third cover comprising the first PTC material;

the coating further being disposed on the second cover and the third cover, the electrical paths further allowing the electric current to be conducted to the second radial bus wire through the second cover and to the third radial bus wire through the third cover with a substantially uniform distribution of the electric current within the first PTC material of each of the second cover and the third cover.

3. The heater cable of claim **2**, wherein the center bus wire is disposed on a central axis of the heater cable, and wherein the first radial bus wire, the second radial bus wire, and the third radial bus wire are further helically wrapped around the center bus wire at a substantially constant number of wraps per foot of length of the heater cable.

4. The heater cable of claim **2**, wherein:

the jacket is disposed over and contains the center bus wire, the first radial bus wire, the second radial bus wire, and the third radial bus wire, the jacket defining a first interstitial space between the first radial bus wire and the second radial bus wire, a second interstitial space between the second radial bus wire and the third radial bus wire, and a third interstitial space between the third radial bus wire and the first radial bus wire; and

the heater cable further comprises an interstitial filler material disposed in the first interstitial space, the second interstitial space, and the third interstitial space.

5. The heater cable of claim **1**, wherein the center bus wire and the first radial bus wire are twisted with each other around a central axis of the heater cable.

6. The heater cable of claim **1**, further comprising a second cover encapsulating the center bus wire, the second cover comprising a second PTC material;

the coating further being disposed on the second cover, the electrical paths further allowing the electric current to be conducted through the second cover with a substantially uniform distribution of the electric current within the second PTC material of the second cover.

7. A heater cable comprising:

a center bus wire extending axially along a central axis of the heater cable;

at least one radial bus wire extending axially through the heating cable and positioned adjacent to the center bus wire;

a first positive temperature coefficient (PTC) material encapsulating at least one of:

the center bus wire; and

one or more of the at least one radial bus wire;

an electrically conductive interstitial material disposed on the first PTC material, the interstitial material forming one or more electrical paths for an electric current carried by the center bus wire to be conducted to the at least one radial bus wire through the first PTC material with a substantially uniform distribution of the electric current within the first PTC material; and

a jacket disposed about the interstitial material, the at least one center bus wire, and the at least one radial bus wire, the jacket comprising a metallic foil layer in electrical contact with the interstitial material.

8. The heater cable of claim 7, wherein the first PTC material encapsulates a first bus wire of the at least one radial bus wire and does not encapsulate the center bus wire.

9. The heater cable of claim 8, wherein the interstitial material coats an outer surface of the first PTC material and contacts the center bus wire.

10. The heater cable of claim 8, wherein the first bus wire is helically positioned around the center bus wire.

11. The heater cable of claim 8, further comprising a second PTC material encapsulating the center bus wire, the interstitial material further disposed on the second PTC material to cause the one or more electrical paths for the electric current to further be conducted to the at least one radial bus wire through the second PTC material with a substantially uniform distribution of the electric current within the second PTC material.

12. The heater cable of claim 11, wherein the interstitial material is further disposed between the first PTC material and the second PTC material.

13. The heater cable of claim 7, wherein the first PTC material is a polymer-carbon compound.

14. The heater cable of claim 7, wherein the interstitial material is carbon black.

15. A heater cable comprising:

a center bus wire extending axially along a central axis of the heater cable;

at least one radial bus wire extending axially through the heating cable and positioned adjacent to the center bus wire, the at least one radial bus wire being encapsulated with a PTC material; and

an electrically conductive interstitial material disposed around the at least one center bus wire and the at least one radial bus wire, the interstitial material having an electrical resistance substantially less than an electrical resistance of the PTC material;

wherein the center bus wire is a bare wire that is not encapsulated with a PTC material.

16. The heater cable of claim 15, further comprising a jacket disposed about the interstitial material, the center bus wire, and the at least one radial bus wire.

17. The heater cable of claim 15, wherein the PTC material has a plurality of thicknesses along the length of the at least one radial bus wire.

18. The heater cable of claim 15, wherein the at least one radial bus wire is positioned helically about the center bus wire.

19. The heater cable of claim 15, wherein the at least one radial bus wire comprises a first radial bus wire, a second radial bus wire, and a third radial bus wire, each encapsulated by a corresponding cover of a plurality of covers of the PTC material, each of the plurality of covers having an equal thickness.

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